BENWEI LIAO[1], SHUEIWAN H. JUANG[1], HAUCHIEH LIN[2]

A NEW DESIGN OF WET SCRUBBER
FOR REMOVAL OF FINE PARTICLES FROM EXHAUST GAS

Bag-house dust collectors are commonly used in the industry for removing solid particles from dust laden gas. Bag house filter media need to be periodically cleaned in order to remove accumulated particles from the filter surface. Pulse jet cleaning is the most common cleaning method but produces noise increment of about 30–40 dB, which is its major disadvantage. The present study reports on a new type of combined wet scrubber–Venturi scrubber in the shape of a cyclone. The proposed design eliminates the noise associated with the pulse jet filter-cleaning process and filter bag replacement costs. The experimental results were demonstrated with high efficiency in the design.

1. INTRODUCTION

Common methods of cleaning bag filters include mechanical oscillation, backwashing, and pulse jet cleaning. The pulse air backwashing method is usually used to remove dust attached to the filter. However, this cleaning procedure creates noise increment of about 30–40 dB, which is its major drawback. In addition, increasing public environmental awareness and demand for living quality have led to an increasing number of cases involving issues of noise and pollution.

Standard cyclone collectors use a cyclone with tangential inlet. Because of their simple design, easy operation, low maintenance cost, and ability to withstand high concentrations of dust and function at high pressure and high temperature, such collectors

_____

[1]Mechanical and Mechatronic Engineering of the National Taiwan Ocean University, Beining Rd. 2, Jhongjheng District, Keelung City 202, 20200 Taiwan, R.O.C., corresponding author S. Juang, e-mail: shjuang@mail.ntou.edu.tw

[2]Environment, Safety and Hygiene Division of the Unimicron Technology Corporation, Shan Ying Rd. 177, Kwei Shan Industrial Park, Taoyuan, 33300 Taiwan, R.O.C.

are usually used for initial stage of dedusting in industrial applications. Filtration equipment do not generally produce particle bounce by cyclone [1] in use, and the dust collection efficiency curve of such equipment is similar to that of the traditional respirable sampling apparatus [2]. Therefore, these filters are usually used for respirable particle sampling.

The fundamental principle of the cyclone collector is as follows: when air entering the collector is forced to spin, large particles, influenced by centrifugal forces, will deviate from the flow line and reach the wall of the collector to accumulate in the dust bag, and clean air will be exhausted from the cylinder. For particles with an aerodynamic diameter higher than 30 μm, the removal efficiency of the cyclone collector can reach 99%. However, removal efficiency is very low for particles with aerodynamic diameters lower than 5 μm. Therefore, such apparatus is used when coarse dust or high concentration of dust needs to be removed, or when high collection efficiency is not required.

A wet scrubber uses liquid to remove particles or harmful gas. Water is sprayed directly onto waste gas or the gas is passed through a water film or mist, so that the particulates are captured within water droplets. These methods effectively remove dust particles as well as harmful gases such as SO_x. The wet scrubbing method is often used when dust and gaseous pollutants need to be removed simultaneously. With the exception of the Venturi scrubbers, all types of wet scrubbers have poor removal efficiency for particles with aerodynamic diameter lower than 1 μm.

The separation of fine particles from exhaust gas is an important gas cleaning process. Venturi scrubbers are efficient wet collectors for particle control in which the particle collection efficiency depends largely on the pressure drop. The literatures include extensive research on the separated efficiency and pressure drop characteristics of the Venturi scrubbers [3–5]. They have high dust collection efficiency and low maintenance cost, and can be used to remove micron sized as well as submicron particles. However, high levels of energy are required to collect smaller particles, thereby increasing operating costs. The Venturi system comprises three main sections such as convergence, throat, and divergence sections. The liquid injected into the wall of the scrubber is sheared by the action of high-speed airflow produced when the inlet gas enters the narrow throat. This produces many small liquid droplets, which are collectors for dust particles. The dust collection efficiency can be improved by increasing the inertial impaction mechanism. Therefore, Tsai et al. [6] and Huang et al. [7] proposed improving the dust collection efficiency of the Venturi scrubber by heterogeneous nucleation, where the water is replaced by steam, in order to reduce loss of pressure. Their findings showed that the traditional Venturi scrubber has poor dust collection efficiency for submicron particles. However, if these particles can be increased to micron size via heterogeneous nucleation, they can be removed with high efficiency at a reasonable pressure drop. Therefore, the equipment studied in this work offers many advantages over traditional designs in terms of. the elimination of backwashing noise and the cost of replacing the filter bag.

2. EXPERIMENTAL SETUP

As shown in Fig. 1, the proposed design combines the structural characteristics of a cyclone collector and the Venturi scrubber.

Fig. 1. Characteristic shape of proposed wet scrubber

The general design comprises a main body, scrubbing tower, sieve plate, watering device, catch basin and dust collection device (Fig. 2). The main body is equipped with an air inlet and an air outlet. The scrubbing tower is within the main body. The first air passage (Fig. 3) forms between the outside wall of the scrubbing tower and the inner wall of the main body. The second air passage forms in the scrubbing tower, at the bottom of which is an opening that connects the first air passage to the air inlet and the second air passage (Fig. 4). The second air passage is connected to the air inlet. The sieve plate and nozzles are mounted in the second air passage. The sink is located below the inlet of second air passage. The dust collection device is below the main body, and is connected to the first air passage.

The equipment removes dust in two stages. In the first stage, waste gas containing dust is drawn into the first air passage, where the centrifugal force of the cyclonic collector causes large dust particles to drop into the dust collecting device. The remaining waste gas, containing smaller dust particles, then enters the scrubbing tower from the

opening at its base, and the fine particles are collected and removed from the waste gas by water droplets produced by the nozzle.
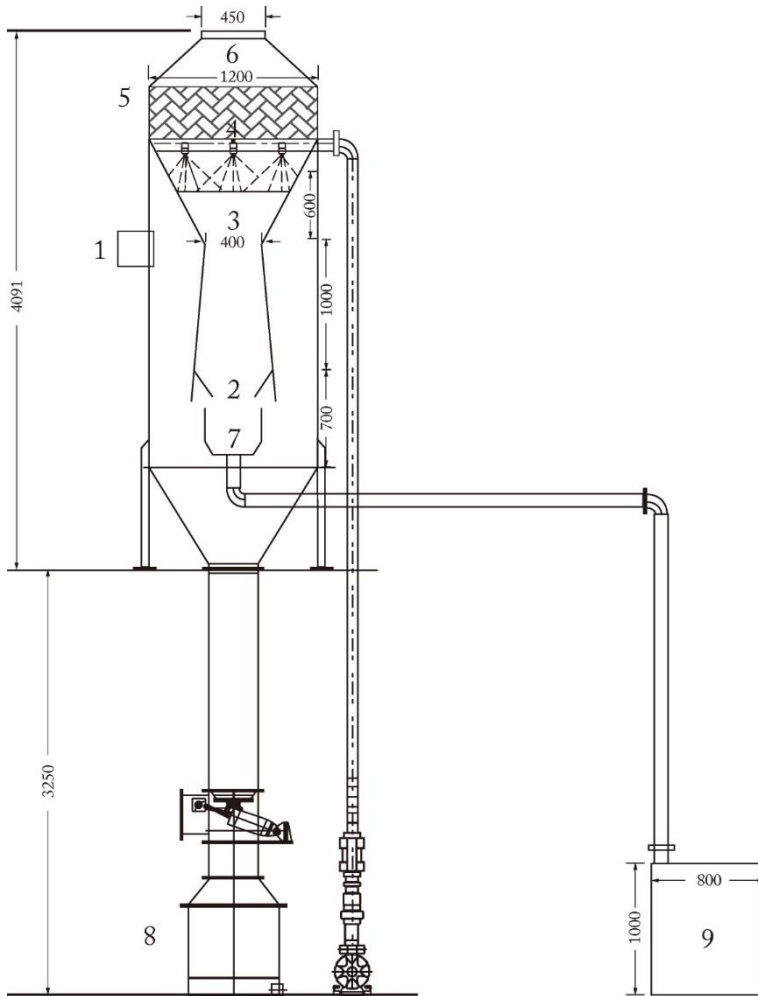

Fig. 2. Scheme of the dust collecting and cleaning equipment: 1 – air inlet (first air passage), 2 – second air passage, 3 – sieve plate, 4 – nozzle supplying water, 5 – demister, 6 – air outlet, 7 – sink, 8 – collector for dry dust (from the first stage), 9 – slurry accumulation vessel (from the second stage)

The present study examines the dust removal efficiency of this two-stage dust collector under conditions of constant airflow rate (50 m^3/min) but for various liquid gas (L/G) ratios defined as dm^3/min per m^3/min (1, 0.7, and 0.5 dm^3/m^3), and compares the size distribution of particles after the two stage dust removal. The various L/G ratios are decided by the pressure drop and removal efficiency. Because the higher ratio (over

1 dm^3/m^3) will cause bigger pressure drop than traditional device and the lower ratio (below 0.5 dm^3/m^3) will cause low removal efficiency.

Fig. 3. Picture of the first air passage   Fig. 4. Picture of the second air passage
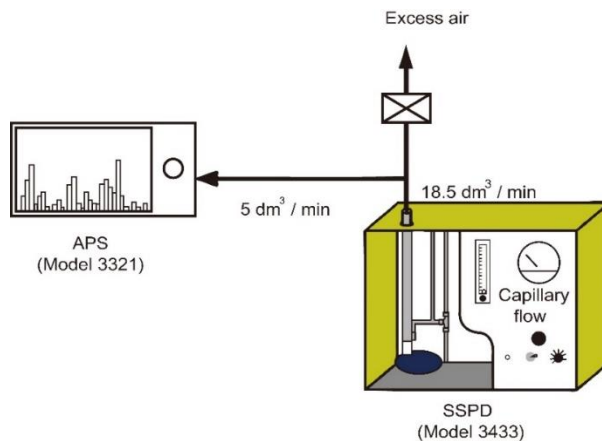

Fig. 5. Flow diagram of the dust dispersion experiment

The removal efficiency of the dust collector is measured using two groups of micro-orifice uniform-deposit impactors (MOUDI 10) which conduct synchronous sampling at the entry and exit ends of the dust collector. Figure 5 shows a flow diagram for the dust dispersion experiment. The small scale powder disperser (SSPD, Model 3433, MN, USA) is designed to efficiently disperse small quantities of dry powder in the diameter range of 1–50 μm. The SSPD has been designed to operate as a standalone powder disperser or, when used with the aerodynamic particle sizer (APS), as a powder sizing system.
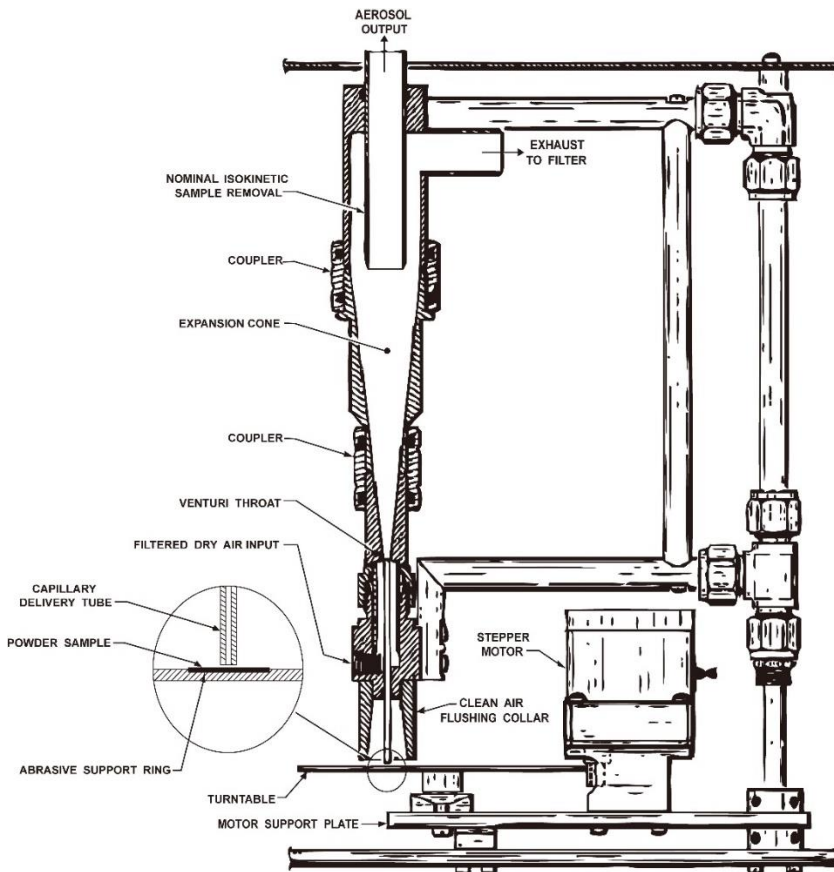
Fig. 6. Aluminium disk

Fig. 7. Schematic diagram of the experimental system (SSPD)

The dust to be tested is distributed uniformly in the aluminum disk (Fig. 6) which contains three concentric, V-type circular grooves. A weighed quantity dry powder is carefully loaded into appropriate grooves using a razor blade or knife as the packing tool. The disk is then placed on the support shaft of the SSPD which disperses the test dust evenly, with sufficient shear stress provided by the disperser at an operating flow of 18.5 dm^3/min. An aerodynamic particle sizer (APS, Model 3321, MN, USA, Fig. 7) is subsequently used to determine the size distribution of particles dispersed by the SSPD.

Particles on the turntable of the SSPD are drawn to the Venturi throat by the Venturi aspirator and capillary delivery tube, and are dispersed by a vigorous turbulence and high hydrodynamic stresses inside the Venturi throat (where gas velocity is very high and pressure is low). However, when the SSPD is used, a large amount of the particles is accumulated within the Venturi throat. Due to this fact, the long-term operation of the device is not possible.
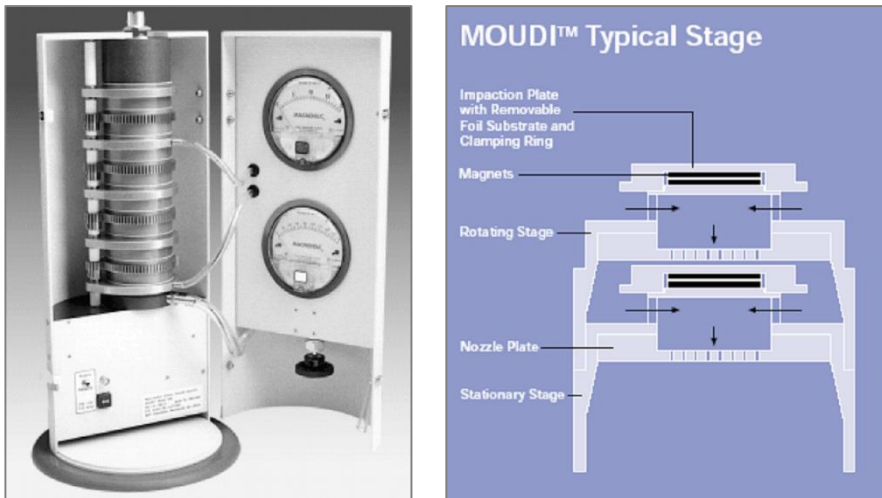

Fig. 8. Microorifice uniform deposit impactor (MOUDI)

Figure 8 shows a photograph and an internal structure diagram of the 10 stage MOUDI. Each stage includes nozzles of different diameters, in descending order from stages zero to nine, where particles of different size are collected. The number of nozzles range from 1 for the inlet to 2000 for the lower stage with the nozzle diameter ranging from 1.71 cm to 52 μm. Very small nozzles (microorifices) have been used to obtain cut sizes as small as 0.056 μm with a moderate pressure drop. A rather high flow rate (30 dm^3/min) has been achieved by using a large number of nozzle per stage. Even though there is a large number of nozzles, the impaction surface area is only 2.7 cm in diameter. The particles deposit in mounds below each nozzle. By rotating the impaction plates relative to the nozzles, the deposits from each nozzle are annular rings. By placing

the nozzles at prescribed distances from the center of rotation, the rings will overlap, forming a uniform deposit on the impaction plate. These different size particles have differing inertia in the same airflow. When the collected gas passes the orifice, the particles will accelerate as the flow of gas speeds up. Larger particles have greater inertia, which causes them to directly impact the filter paper on the collection plate. Particles with lower inertia will continue to the next fraction. The sampling flow indicated by the MOUDI manufacturer is 30 dm^3/min, and particle samples are size-fractionated (from the top down) as: 18, 10, 5.6, 2.5, 1.8, ratio, 0.56, 0.32, 0.18, 0.10, 0.056, and <0.056 µm (after filter).

The purity inside the aerodynamic diameter analysis meter was tested. The test lasted 30 sec at a flow rate of 5.0 dm^3/min. The test result is acceptable if the mean concentration of the APS is less than 0.01 particle/cm^3. The air leakage test was conducted to instrument before being used in this experiment. A pressure gauge was connected to the front end of the instrument. The pressure was adjusted to -30 cm Hg via a vacuum pump connected to the rear of the instrument, and then the valve was closed between the experimental system and the pump. The leak detection standard requires that the vacuum gauge reading is equal to or greater than 20 cm Hg after 10 min.

The particle collection plate used by the MOUDI is an aluminum foil 47 mm in diameter. Prior to use, the aluminum foil was conditioned at a temperature of 22.0±1 °C and 40.0±5% humidity for at least 24 h. In addition, a high-precision balance (Sartorius CP2P-F; minimum weight 0.001 mg, readings accurate to 6 decimal places) was used to weigh the filter paper. The experimental setup also used silicon grease on the impact substrate of the MOUDI (Shin-Etsu Chemical Co., Ltd., KF96SP, Kyoto, JP) in order to prevent particle-bounce.

3. RESULTS

Figure 9 shows the size distribution of particles (produced by laser drilling, machine drilling, plate cutting and abrasive machining, e.g. CNC substrate cutting dispersed by the SSPD). The median diameters (NMD) of the four types of particulates are 1.48, 1.84, 2.45 and 2.12 µm, respectively, indicating that the plate-cutting process produces the largest particles.

The results obtained from MOUDI 10 are shown in Figs. 10–12. Figure 10 shows the particle size distribution at the inlet of the proposed dust collector. The study will focus on the particles of CNC substrate cutting process, and the diameter of particles is almost greater than 1 µm. Figure 11 shows the particle size distribution at the outlet of the dust collector for an airflow rate of 50 m^3/min and L/G ratios are equal to 1 dm^3/m^3, 0.7 dm^3/m^3, and 0.5 dm^3/m^3. The results show that in all cases the concentrations of discharged dust is less than 150 µg/m^3. The efficiency of the new type of scrubber reaches approximately 99.9% when the particle size is approximately 1 µm or larger. Figure 12 shows that submicron particles are partly removed because when the exhaust

gas flows into the second air passage, they will be washing-down by Venturi scrubber mechanism.
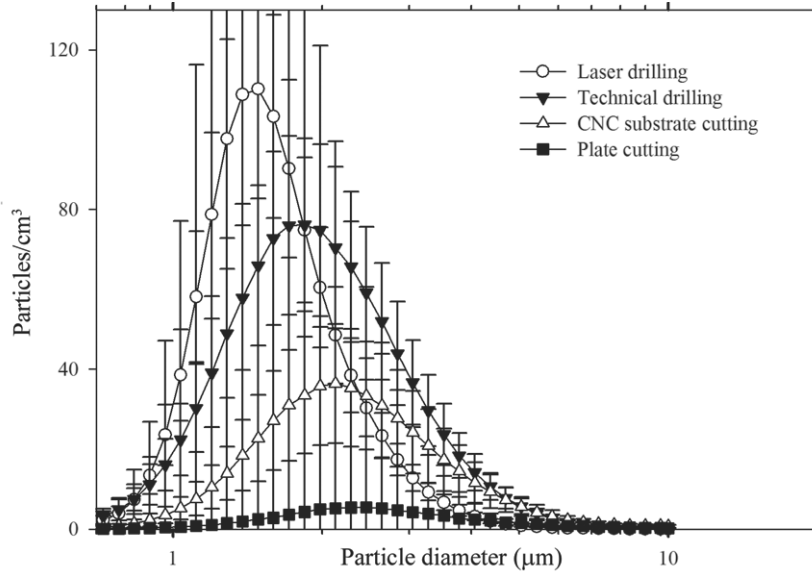

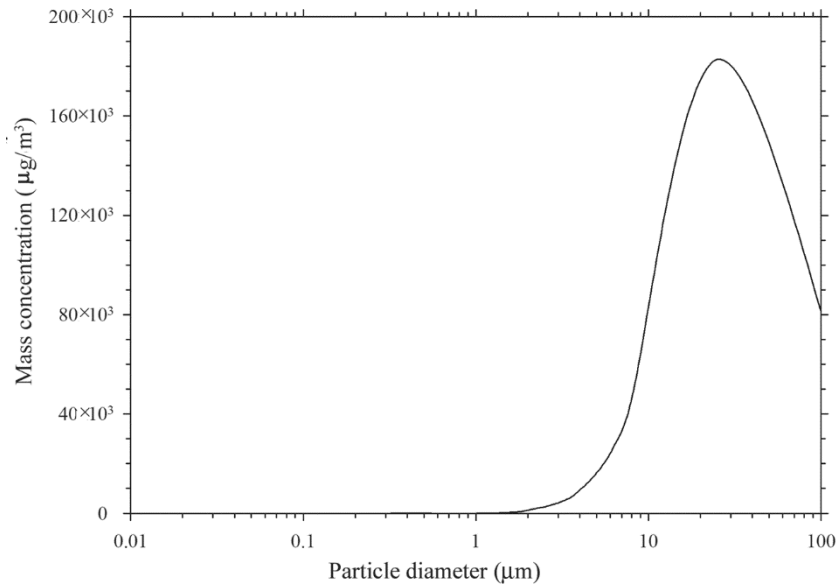Fig. 9. Size distribution of particles produced by various drill processes

Fig. 10. Size distribution of inlet particles
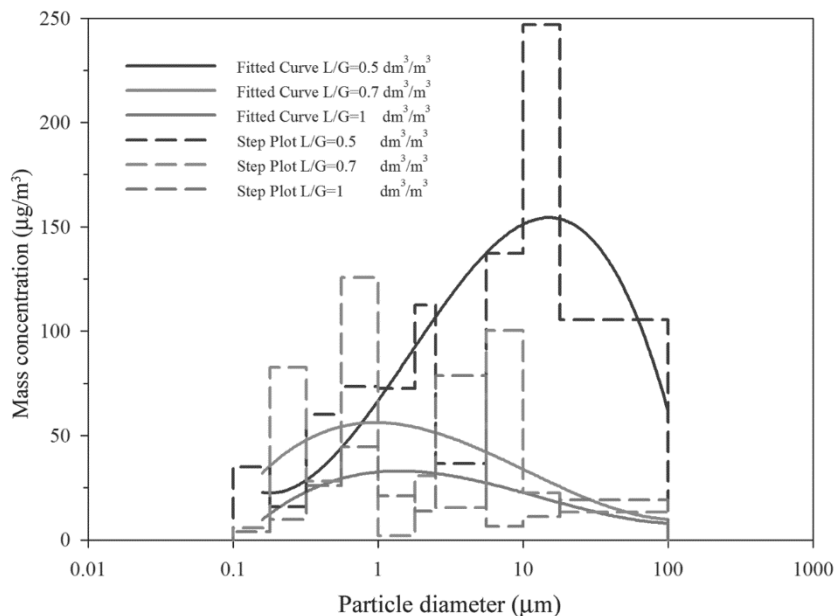for the proposed dust collector at the airflow rate of 50 m³/min

Fig. 11. Size distribution of outlet particles
for the proposed dust collector at the airflow rate of 50 m^3/min

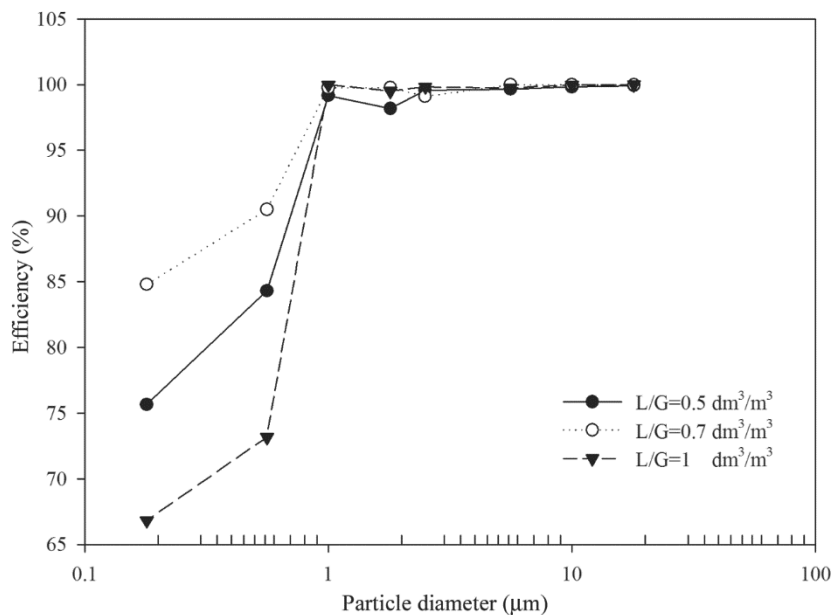Fig. 12. Removal efficiencies for the proposed
dust collector at the airflow rate of 50 m^3/min

Table 1

Removal efficiency by SGS and corresponding pressure loss

Inlet concentration [mg/Nm^3]	Outlet concentration [mg/Nm^3]	Removal efficiency [%]	Pressure loss [Pa]
20.9	2.15	89.71	539
1600	1.86	99.88	1323
7680	2.04	99.97	1764

Table 1 shows the removal efficiency and pressure loss at the airflow rate of 50 m^3/min and $L/G = 1$ dm^3/m^3. The inner structure of proposed wet scrubber is same with the shape of the Venturi scrubber. Particle removal efficiency increases with increasing pressure drop because of increased turbulence due to high gas velocity in the throat. But the same airflow rate of the inlet and L/G ratio, the pressure drop is increased with increasing exhaust gas concentration. The increasing exhaust gas concentration will cause the lower dynamic pressure in the inner wall because it will lead to more collisions with water droplets in the throat. The pressure loss of the proposed wet scrubber is the same or slightly greater than that of the bag-house method.

4. CONCLUSIONS

The proposed wet scrubber described here combines the concepts of a Venturi scrubber and cyclonic collector. It differs from a Venturi scrubber in that it magnifies the throat size of the Venturi is significantly larger comparing to traditional one in order to reduce the pressure drop during operation. According to the experimental results, the collection efficiency of this new dust collector can exceed 99%, which is equal to or greater than that of the traditional bag collector. However, the proposed design is capable to operate continuously (unlike the bag filter, which requires periodical regeneration and replacement), thereby considerably reducing costs. In addition, the two-stage method does not generate the noise associated with the reverse flow.

REFERENCES

[1] COHEN B.S., HERING S.V., *Air sampling instrumentsfor evaluation of atmospheric contaminants*, 8th Ed. American Conference of Governmental Industrial Hygienists, Inc., Cincinnati 1995.
[2] HINDS W.C., *Aerosol Technology, Properties, Behavior, and Measurement of Airborne Particles*, 2nd Ed., Wiley, 1999.
[3] CALVERT S., *Venturi and other atomizing scrubbers efficiency and pressure drop*, AICHE J., 1970, 16, 392.
[4] MAYINGER F., NEUMANN M., *Dust collection in Venturi scrubbers*, Ger. Chem. Eng., 1978, 1, 289.
[5] TIGGES K.D., MAYINGER F., *Experiments with highly efficient Venturi scrubbers for aerosol separation from gases under multi-plane water injection*, Chem. Eng. Process, 1984, 18, 171.

[6] TSAI C.J., LIN C.H., WANG Y.M., *An efficient Venturi scrubber system to remove submicron particles in exhaust gas*, J. Air Waste Manage. Assoc., 2005, 55, 319.

[7] HUANG C.H., TSAI C.J., WANG Y.M., *Control of submicron particle collection efficiency in a Venturi scrubber. Comparison of experiments with theory*, Env. Sci. Tech.*,* 2007, 20, 237.